Appendix 6

FM Modulation Increasing Baseband Noise In The Presence of An IBOC Digital Signal

I. Introduction

Certain types of VHF In-Band/On-Channel (IBOC) digital audio broadcasting (DAB)systems transport digital audio information on independent adjacent RF signals on either side of the host FM signal. In conventional FM stereo broadcasting, normal deviation of the carrier (modulation) does not significantly contribute to the recovered composite baseband noise floor in a receiver. During laboratory testing of IBOC DAR systems of the type utilizing the adjacent RF signals, modulation of the main analog channel caused an increase in the recovered composite baseband noise floor when the adjacent DAR signals were present.

II. Background

Testing by the Electronic Industries Association's Consumer Electronics Manufacturers Association (EIA/CEMA) DAR Laboratory revealed an unexpected increase in recovered baseband noise when FM modulation occurred in the presence of IBOC DAR system signals of the proposed types using adjacent RF signals. These IBOC systems transmit digital audio at a reduced power level in the first adjacent channels and combine the digital and analog signals at the RF output of the transmitter (see Figure 1).

The noise floor increase was initially detected during the set up and measurement of subcarrier (SCA) performance with and without the DAR signal. During the set up and calibration of analog modulation with the IBOC digital signal, it was observed that *without* analog modulation the baseband noise increase ranged from 15 to 20 dB; *with* analog modulation, the increase was, significantly, 40 dB.

III. Testing

Follow-up testing to explore causes of the 40 dB increase in noise relied upon using a professional SCA receiver, a wideband modulation receiver/analyzer, a spectrum analyzer and synthesized signals. SCA receivers recover information (audio or data) transmitted on subcarrier frequencies typically from 57 kHz to 92 kHz inserted into the composite baseband by the broadcaster. Tests using the SCA receiver revealed that the SCA signal-to-noise ratio is not only impacted by the presence of the digital signal, but also by the addition of main channel modulation (with DAR). Under these conditions, SCA signal-to-noise performance would be reduced by as much as 33 dB. This is significant because main channel modulation would not normally affect SCA performance except under dynamic signal conditions like multipath, which even then would not cause much degradation. Tests with the modulation analyzer showed that the composite baseband noise floor is noticeably increased by the addition of main channel modulation, especially in the regions above 40 kHz.

Testing showed that the RF and IF spectrums were free of distortion and spurious signals with no encroachment of one signal on another. Further testing with other modulation analyzers showed that the baseband noise increase was not limited to, or an anomaly of, one particular type of receiver.

Additional tests substituted the DAR signal with synthesized CW and modulated signals to study the interaction of multiple RF signals at the composite level. The complex DAR signals were replaced with a CW signal (RF1) positioned 200 kHz away from the center of the main channel (RF1). Viewed on a spectrum analyzer the recovered baseband spectrum showed the resultant component at 200 kHz (see Figure 2). Modulation of RF2 resulted in the deviation appearing on the component at 200 kHz (see Figure 3). The same modulation of RF1, while RF2 was not modulated, resulted in precisely the same baseband signature with the component at 200 kHz *appearing* to be modulated even though it was not. More testing showed that modulation of the main channel (RF1) mathematically *added* itself to any existing modulation of RF2 resulting in the component at 200 kHz to appear to have more deviation than it really had, if any. What was demonstrated was that the component at 200 kHz represents the difference between the two RF signals and that frequency modulation -- an instantaneous difference in frequency -- is mirrored in the recovered adjacent component.

As a final investigative step, mathematical modeling of the limiter and FM detector resulted in similar findings under the same signal conditions.

IV. Conclusion

The test results revealed that the characteristics of the limiter and FM detector may be the mechanisms responsible for increasing noise with modulation in the presence of a non-coherent adjacent RF signal. The design of a detector for FM broadcast receivers is normally wideband in nature, typically from 600 kHz up to 1 MHz in bandwidth. This bandwidth is required in order to keep the phase delay of the composite stereo signal, especially the L-R sidebands, very low in order to recover a high quality stereo signal. With the non-linear process of limiting in the limiter section and detector containing non-linear devices, mixing of the two signals occurs. The detector is essentially a mixer with one input being a variable phase-shifted version of the other. If two input signals fall into the linear range of the detector, the output will be proportional to the frequency difference between them.

For example, when signals at 94.1` MHz and 94.2 MHz are applied to an FM receiver, a the detector output will be 100 kHz and harmonics of 100 kHz. Modulation of either carrier will show as modulation (or additional modulation) of the 100 kHz beat, as well as the modulation of the specific carrier. When the undesired adjacent RF signals are modulated, the main channel modulation will effectively be added to any adjacent component recovered by the detector. If the proximity or spacing of the signals is too close, the *added* modulation of the recovered adjacent component caused by the mixing action will "spill" into the composite baseband region and increase baseband noise.

This has implications for implementing IBOC DAR systems.

Figure 1

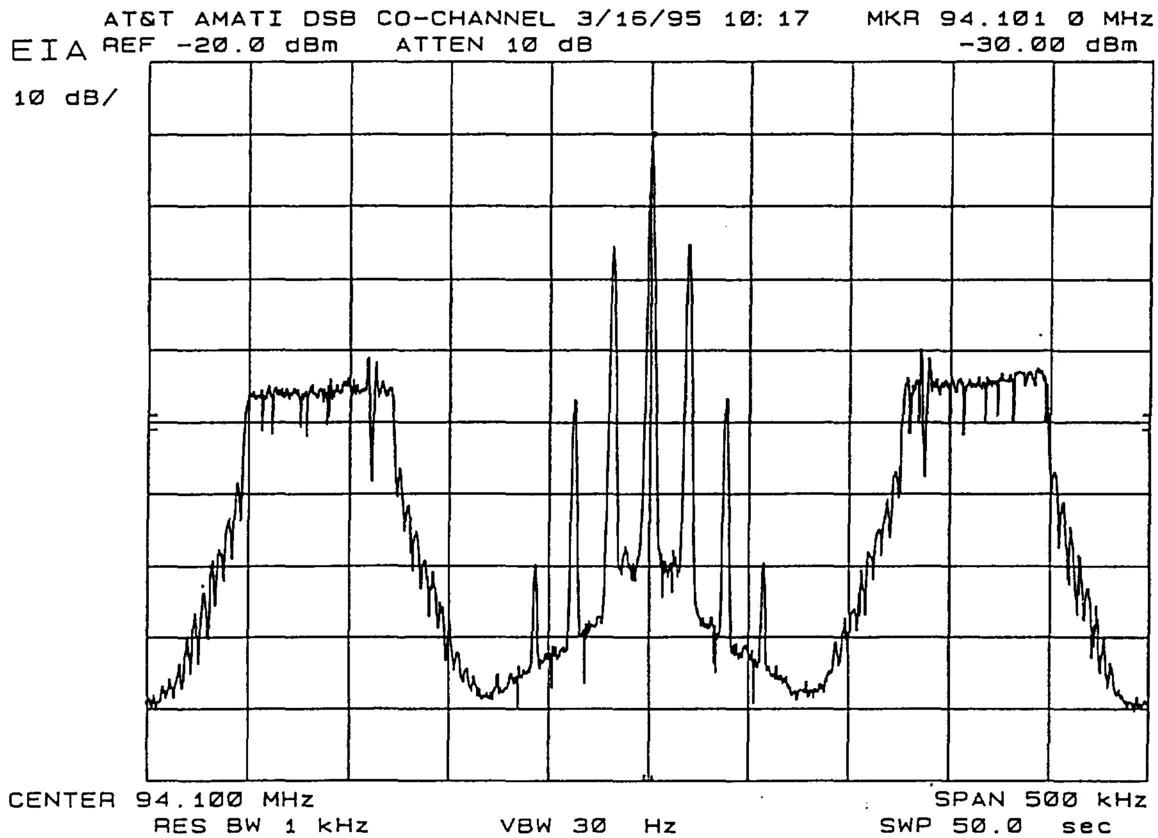
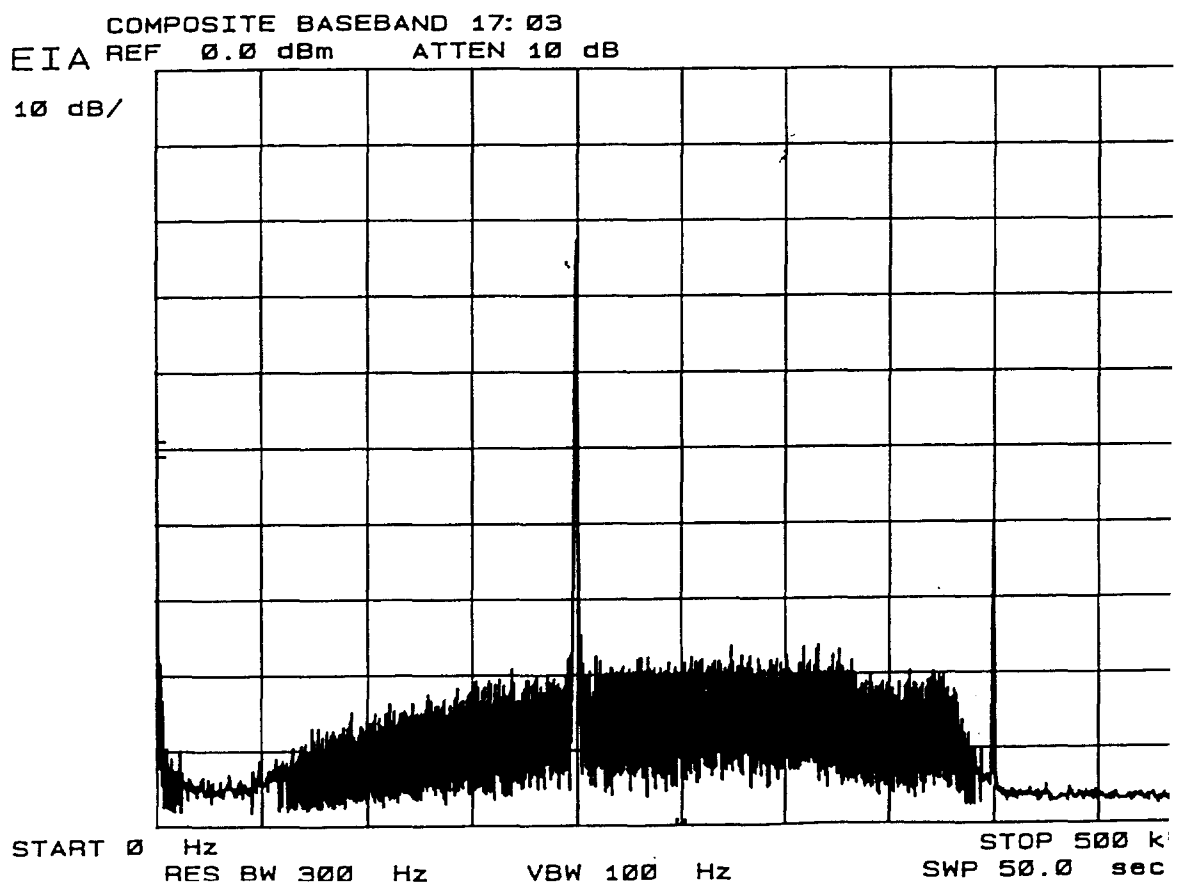


Figure 2



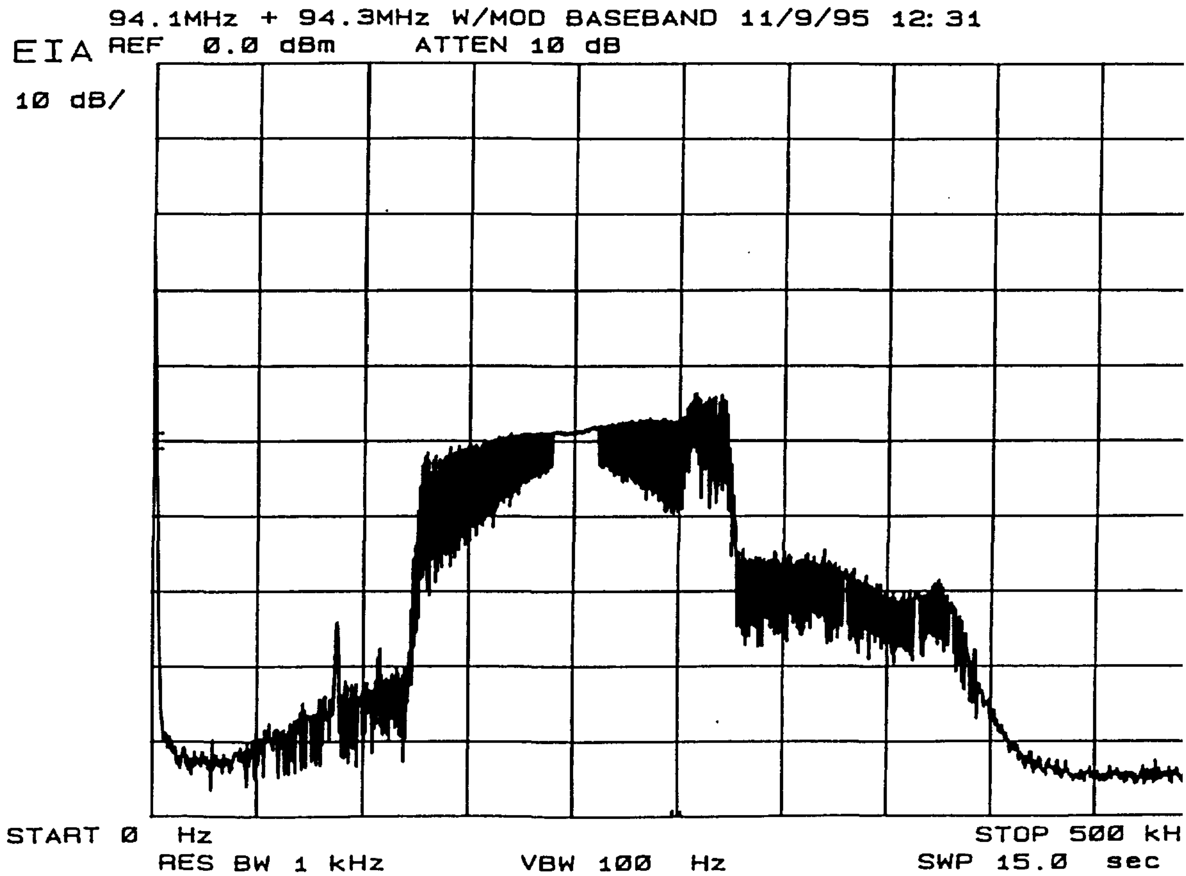

94.1MHz + 94.3MHz W/MOD BASEBAND 11/9/95 12:31
EIA
REF 0.0 dBm
ATTEN 10 dB
10 dB/
START 0 Hz
STOP 500 kH
RES BW 1 kHz
VBW 100 Hz
SWP 15.0 sec

Figure 3

Appendix 7

In-Band Digital Sound Broadcasting Subcarrier Tests

I. Introduction

Two of the FM In-Band/On-Channel (IBOC) Digital Audio Radio (DAR) systems transmit the digital audio on independent upper and lower first adjacent RF signals. During laboratory testing of the adjacent channel IBOC DAR systems, a significant increase in the 92 kHz analog subcarrier noise floor was observed. This noise existed only when the main channel was modulated and with the digital signal present. Controlled conventional main channel modulation does not significantly contribute noise to FM subcarriers. For more information on the theory of this problem, refer to Appendix 6.

II. General Description of Tests

These tests compared the conventional FM station analog and digital subcarrier performance with that of a station transmitting the IBOC digital signal. Strong (-47 dBm) and weak (-77 dBm) signal levels were used for the tests. The tests were also conducted with simulated multipath. The results multipath are not included in the document. RMS noise measurements were used for the analog subcarriers. The main program channel was modulated with clipped pink noise. Total modulation for the analog channel was set for 110%.

The IBOC to FM subcarrier tests were conducted for the IBOC systems using three different subcarrier groups:

Group A: 57 kHz RBDS 3% injection, 66.5 kHz HS digital (Seiko) 8.5% injection, and 92 kHz FM 8.5% injection.

Group B: 57 kHz RBDS 10% injection and 67 kHz analog 10% injection.

Group C: Not used in this test series.

Group D: 92 kHz digital (Mainstream Data) 10% injection

III. Test Results

The test results without multipath are shown in Table 1. The subcarrier data on the FM line is the reference without the digital signal. For the -47 dBm signal level tests, the two systems transmitting the digital signal in the first adjacent channels showed a 26 dB increase in the noise floor for the 92 kHz analog subcarrier. The 57 kHz RBDS and 66.5 kHz digital subcarriers were not effected by the addition of the digital signal. The 67 kHz FM subcarrier noise floor was increased by 4 dB.

The weak signal level (-77 dBm) was too low for the 66.5 and 92 kHz subcarriers to operate. The 92 kHz subcarrier showed a 6 dB increase in noise floor with the IBOC systems that transmit the digital in the upper and lower first adjacent channels.

IV. Receivers Used for the Tests

SERVICE	RECEIVER
57 kHz RBDS:	Denon TU-380D
66.5 kHz Digital:	Seiko RPA
67 kHz Analog:	Compol SCA receiver
92 kHz Analog:	Compol SCA receiver
92 kHz Digital:	Mainstream Data

V. Ancillary Data

Each of the DAR systems incorporates an ancillary data channel within the digital audio channel. The BER for this channel was measured with the interference set at the level that produced TOA for each of the noise and co-channel impairments.

EIA Digital Audio Radio Test Laboratory

Test L-2 & L-3 Subcarriers DAR -> Host SC		Composite Subcarrier Group A			Composite Subcarrier Group B		Group D		
		57 KHz RBDS 3% ERRORS MAX:(%)	66.5 KHz HS Data 8.5% ERRORS log BER	92KHz Analog 8.5% S/N (dB)	57KHz RBDS 10% ERRORS MAX:(%)	67KHz Analog 10% S/N (dB)	92KHz Digital 10% SS # FEC1	#FEC2	SQ #UNC
FM	Strong Signal Level (-47 dBm)	0	-6	46	0	45.3	210 0	 0	170 0
AT&T / Amati DSB	Strong Signal Level (-47 dBm)	0	-5.95	20	0	41	209 1290	 4558	92-130 455
AT&T / Amati LSB	Strong Signal Level (-47 dBm)	0	-6	27	0	43	209 1310	 4272	76-130 475
USADR FM1	Strong Signal Level (-47 dBm)	0	-5	20	0	41	209 1350	 6199	58-109 288
USADR FM2	Strong Signal Level (-47 dBm)	0	-5.3	32.5	0	43.2	210 0	 0	167 0
FM	Weak Signal Level (-77 dBm)	0	NA	22.4	0	35.4	113 NA	 NA	0 NA
AT&T / Amati DSB	Weak Signal Level (-77 dBm)	0	NA	16	0	34		NA	
AT&T / Amati LSB	Weak Signal Level (-77 dBm)	0	NA	18	0	34.5		NA	
USADR FM1	Weak Signal Level (-77 dBm)	0	NA	16	0	33.5		NA	
USADR FM2	Weak Signal Level (-77 dBm)	0	NA	19.9	0	34.6		NA	

NOTES:
* Digital SCA's graded as the number of observed errors within a five minute period.
* 57KHz RDS: Error = Percentage of maximum block errors indicated by MAX:(%) in the RDS CHECKUP utility
* 66.5KHZ Seiko: Error = Average log BER observed on the Seiko RPA utility with a print-out of a typical 20 sec. segment
* 92KHz Mainstream: Error = # FEC1, # FEC2, # Blocks Uncorrected(#UNC) figures, as indicated on the Mainstream receiver. Failure considered as > 5 first layer errors (# FEC1) in a five minute period.
* Main channel modulation: Abba
* NA = RF level too low for proper operation

EIA Digital Audio Radio Test Laboratory

Test L-4 Subcarriers DAR -> Host SC Moderate Signal Level		Composite Subcarrier Group A			Composite Subcarrier Group B		Group D		
		57 KHz RBDS 3% ERRORS	66.5 KHz HS Data 8.5% (log BER)	92KHz Analog 8.5% EO&C	57KHz RBDS 10% ERRORS	67KHz Analog 10% EO&C	92KHz Digital 10% ERRORS # FEC1	# FEC2	# UNC
FM	Urban Slow Rayleigh	2	-5.5	Good audio, medium noise and some main chan. audio noise detected during fades	0	Good audio with mild noise during fades. Weak main ch. audio noise heard during fades	110	142	3
AT&T / Amati DSB	Urban Slow Rayleigh	4	-5.2	Poor audio (raspy) with main chan. audio noise heard at all times - worse during fades Unusable audio	2	Good audio with mild main channel audio noise heard during the fades Usable audio	1274	4608	524
AT&T / Amati LSB	Urban Slow Rayleigh	4	-4.8	Fair audio quality with main channel audio noise heard in background most of the time Usability: Marginal	3	Good audio with mild main channel audio heard during the fades Usable audio	1334	1325	219
USADR FM1	Urban Slow Rayleigh	3	-4.5	Poor audio (raspy) with main chan. audio noise heard at all times - worse during fades Unusable audio	3	Fair audio with mild main channel audio at all times - more during fades Usable audio	1333	5494	626
USADR FM2	Urban Slow Rayleigh	2	-3.8	Fair audio - noisy (hiss) most of the time - worse during fades usable audio	1	Good audio with mild noise during fades Usable audio	965	1023	106
FM	Urban Fast Rayleigh	11	-2.6	Good audio with medium multipath type spits Usable audio	8	Good audio with mild multipath type spits Usable audio	271	527	245
AT&T / Amati DSB	Urban Fast Rayleigh	12	-2.3	Poor raspy audio with severe tearing sounds. Main chan. audio noise heard at all times Unusable audio	9	Fair audio with medium multipath type spits Usable audio	318	684	300
AT&T / Amati LSB	Urban Fast Rayleigh	12	-2.4	Fair audio quality - noisy with some main channel audio noise Usabilty: Marginal	11	Fair audio with medium multipath type spits Usable audio	273	644	249
USADR FM1	Urban Fast Rayleigh	13	-2.1	Poor raspy audio with severe tearing sounds. Main chan. audio noise heard at all times Unusable audio	9	Fair audio with medium to heavy spitting or tearing noise Usability: Marginal	294	716	257
USADR FM2	Urban Fast Rayleigh	1	-1.9	Fair audio quality -noisy with faint whine in background Usable audio	0	Good audio with medium multipath type spits Usable audio	254	405	238

NOTES:
- Digital SCA's graded as the number of observed errors within a five minute period.
- 57KHz RDS: Error = Percentage of maximum block errors indicated by MAX:(%) in the RDS CHECKUP utility
- 66.5KHZ Seiko: Error = Average log BER observed on the Seiko RPA utility with a print-out of a typical 20 sec. segment
- 92KHz Mainstream: Error = # FEC1, # FEC2, # Blocks Uncorrected(#UNC) figures, as indicated on the Mainstream receiver. Failure considered as > 5first layer errors (# FEC1) in afive minute period
- Analog SCA quality: EO&C of 1KHz audio quality
- Main channel modulation : Abba
- Mainstream data not valid - Rx not in lock during multipath

International Telecommunication Union
Radio Communication Study Groups
Working Party 10B

Document 10B/USA-L
September 4, 1996
Original: English

UNITED STATES OF AMERICA

Update on In-Band On-Channel Digital Sound Broadcasting Development

I. Introduction

The development of IBOC-DSB continues to proceed. Testing has revealed several criteria critical to the practical acceptance of IBOC-DSB. This paper describes those criteria as well as various design strategies being used to address these acceptance criteria.

II. Progress to Date

IBOC-DSB has been under development since 1990. IBOC-DSB systems have either claimed or demonstrated various audio codec rates, digital audio fidelity, signal-to-noise performance, digital signal coverage, non-interference with existing analog broadcast signals and performance in interference environments [1-8].

III. Critical Acceptance Criteria

Recent studies have scrutinized several DSB systems, including IBOC-DSB, in light of various criteria critical to the practical acceptance of IBOC-DSB [9]. These issues include digital signal audio quality, non-interference with host analog, digital coverage limited by first-adjacent interference, analog coverage impaired by first-adjacent IBOC-DSB interference and digital coverage limited by second-adjacent interference.

IV. Solutions Under Development

Modifications to existing IBOC-DSB systems are being developed which address these critical acceptance criteria.

Digital audio quality is being addressed through advances in audio codec technology [10-12]. Progressive development in audio codec quality versus codec rate has resulted in improved audio quality with respect to codec rate, as well as in reduced codec rates with respect to transcoded audio quality. Each successive reduction in codec rate enables performance improvements in coverage, interference performance or impaired channel performance as a consequence of the reduced data rate throughput required.

Interference of IBOC-DSB to the host analog has been shown to be most significantly a function of unintentional stereo matrix conversion of odd harmonics of the stereo separation carrier [9,13]. The FM stereo separation carrier at 38 kHz has a third harmonic at 114 kHz. Receivers prone to noise injection due to unintentional third-harmonic conversion are susceptible to FM composite noise within ± 15 kHz of 114 kHz (the third harmonic of 38 kHz), or 99 kHz to 129 kHz [14]. RF signals appearing 99 to 129 kHz removed from the carrier are the most likely to appear between 99 and 129 kHz in the FM composite. Because receivers susceptible to this interference currently exist, avoidance of the ± 99 kHz to ± 129 kHz region of the RF spectrum by IBOC-DSB modulation is effective in reducing or eliminating perceived L-R (stereo separation) noise when listening in stereo on the most vulnerable FM receivers [15].

Coverage limitations resulting from first adjacent analog interference pose significant challenges which are being addressed through the use of diversity IBOC-DSB sidebands. While some IBOC-DSB systems propose signals using spectrum on both adjacent channels to transmit the digital information, improved codec performance should enable a single digital sideband to accommodate the entire required transmission capacity. The use of diversity DSB sidebands refers to duplicate information transmission on each (upper and lower) sideband of the host FM signal.

In the case where first adjacent interference limits IBOC-DSB coverage, application of diversity sidebands enables the receiver to extend coverage by choosing the more reliable of the two IBOC-DSB sidebands. In the case where IBOC-DSB is expected to interfere with existing first-adjacent analog signals, the presence of redundant IBOC-DSB sidebands allows for each sideband's power levels to be established (or modified), as a regulatory matter, to balance IBOC-DSB coverage against potential interference to existing analog first-adjacent channels.

Finally, second-adjacent interference is largely controlled by limiting the spectral occupancy of IBOC-DSB modulation to no more than ± 200 kHz removed from the carrier.

V. Conclusion

Issues of digital signal quality, non-interference with host analog, digital coverage limited by first-adjacent interference, analog coverage impaired by first-adjacent IBOC-DSB interference and digital coverage limited by second-adjacent interference have been identified as critical to the practical acceptance of IBOC-DSB. These issues are being addressed in the United States through advances in audio codec technology as well as modulation spectrum planning and the development of diversity-sideband IBOC-DSB modulation.

VI. Notes

[1] Thomas B. Keller, "Summary of FM Band IBOC Laboratory Tests Results" *Proceedings, Annual Broadcast Engineering Conference*, April 13-18, 1996, pp 5-13.

[2] David H. Layer and David Wilson, "IBOC DAB: Its Potential for Broadcasters," *Proceedings, Annual Broadcast Engineering Conference*, April 13-18, 1996, pp 14-20.

[3] David P. Maxson and David K. Murotake, "On-Carrier Digital FM Technology: A New Approach for Digital Audio Broadcasting and Extra High Speed Data Transmission," *Proceedings, Annual Broadcast Engineering Conference*, April 13-18, 1996, pp 21-26.

[4] Kenneth D. Springer, "Multipath Propagation and Fading Statistics for Digital Audio Broadcasting in the VHF and UHF Bands," *Proceedings, Annual Broadcast Engineering Conference*, April 18-22, 1993, pp 229-233.

[5] Skip Pizzi, "Projected Conversion Costs for Digital Audio Broadcasting," *Proceedings, Annual Broadcast Engineering Conference*, April 18-22, 1993, pp 234-239.

[6] John M. Cioffi and John A.C. Bingham, "Digital Sound Broadcast with Auxiliary Overhead Control," *Proceedings, Annual Broadcast Engineering Conference*, April 18-22, 1993, pp 243-248.

[7] Daniel A. Fleisch, A.J. Vigil and Bill J. Hunsinger, "An In-Band On-Channel FM Digital Audio Broadcast System," *Proceedings, Annual Broadcast Engineering Conference*, April 18-22, 1993, pp 249-258.

[8] Skip Pizzi and Robert Culver, "The Current Context for Digital Radio: Climate, Opinion and Activities in the Industry," *Proceedings, Annual Broadcast Engineering Conference*, April 12-16, 1992, pp 139-148.

[9] Thomas B. Keller, David M. Londa, Robert W. McCutcheon and Stanley S. Toncich, "Digital Audio Radio Laboratory Tests: Transmission Quality, Failure Characterization and Analog Compatibility," Electronic Industries Association, Consumer Electronics Group, Volumes I and II, August 11, 1995.

[10]Nikil Jayant, "Status Report on PAC and MPAC: Perceptual Audio Coders from AT&T," *International Academy of Broadcasting*, October 1994

[11]N. Jayant, J. Johnston and R. Safranek, "Signal Compression Based on Models of Human Perception," *Proceedings of the IEEE*, vol. 81, no. 10, October 1993.

[12]Nikil Jayant, "Signal Compression: Technology Targets and Research Directions," *IEEE Journal on Selected Areas in Communications*, vol. 10, no. 5, June 1992.

[13]Shigeki Inoue, Yoshimi Iso and Masanori Ienaka, "High Quality FM Stereo Decoding IC with Birdie Noise Cancelling Circuit," *IEEE Transactions on Consumer Electronics*, vol. CE-27, no. 3, August 1991, pp. 243-253.

[14]Consumer radio receivers used in analog compatibility testing [9] represent a wide range of susceptibility to spurious noise and interference as described in [13]. Receivers susceptible to spurious noise and interference are also vulnerable to noise induced by existing adjacent channel interference. Receiver manufacturers today employ remedies which, applied to the design of receivers to mitigate existing adjacent channel interference, are effective as well in mitigating potential interference of IBOC-DSB with FM stereo [15].

[15]Unintentional stereo matrix conversion of odd harmonics of the stereo separation carrier presently introduces noise due to existing first adjacent channel interference. Receiver manufacturers presently mitigate this interference by including combinations of effective FMIF filtering, FM composite filtering (lowpass below 99kHz) and harmonic conversion cancellation in the design of currently manufactured FM receivers. Today's FM stereo receiver designs often employ at least one of these three interference mitigation techniques, sometimes more, depending on market and cost considerations.

Appendix 9

"IMPROVED IBOC DAB TECHNOLOGY FOR AM AND FM BROADCASTING" Brian W. Kroeger, Westinghouse Wireless Solutions Co., A.J. Vigil, USA Digital Radio, presented and distributed at the September, 1996 Society of Broadcast Engineers convention.

[Permission to reproduce this document was denied by USA Digital Radio. A brief summary follows.]

Evaluations of IBOC systems proposed by USADR revealed deficiencies in measured performance. Compromises in coverage area may be necessary as theoretical limits are approached. Discussed are those weaknesses and certain design modifications and techniques including:

* spread spectrum biorthogonal waveforms with spectral shaping, reduced digital signal injection levels and reduced source coding rate

* waveform analysis and characteristics of autocorrelation and crosscorrelation and equalizer performance, use of Gold codes, OFDM modulation and blend with time diversity

ANALYSIS OF IBOC DAR SYSTEM PROPOSALS

Introduction

A wealth of information has been learned over the past three years through the laboratory testing of the In-Band-On-Channel (IBOC) Digital Radio Systems. These IBOC systems transmit the digital signal in the upper and lower first adjacent channels and are intended to conform with the FCC Power Spectral Density (PSD) mask. The all industry sponsored laboratory tests were performed on three IBOC systems, USADR FM-1, AT&T Amati DSB, and AT&T/Amati LSB. The laboratory tests revealed major digital transmission impairment problems and incompatibilities with the FM analog service for all three systems. The two proposals reviewed in this paper address many of the problems identified in laboratory tests. The first proposal, a paper describing an improved version of the USADR FM-1 system, was presented at the ITU meeting in Spain, and the second proposal was presented at the National SBE Convention last fall (Westinghouse proposal). Significant details of both systems were presented in these papers. Both proposals are variations of the sideband IBOC systems tested in the DAR laboratory. Both proposals take into account system problems revealed in the industry sponsored DAR laboratory tests. Because the new proposal used the same basic in-band-on-channel transmission technique as the systems tested in the DAR laboratory, the laboratory test data can be used to predict the new systems performance.

I System Descriptions

Diversity Sideband IBOC Proposal (Westinghouse)

The complete digital signal is duplicated for each digital sideband. The system will operate on the alternate sideband when interference is present. To reduce digital interference to the analog host or adjacent channel analog signals, the digital power is reduced 6 to 10 dB below the level used for the tested FM-1 system. The two independent digital modulated channels (sidebands) start at a frequency ±100 kHz removed from the channel center frequency and extend to ±200 kHz from the channel center frequency. Stereo audio source coding rate of 96 kbps, and a channel coding rate of 192 kbps is used. A system of time diversity and switch to time delayed analog FM is intended to reduce the effect of in-motion multipath. Because the two signals are not transmitted at the same time, short multipath events effecting the digital signal will be hidden by the switch to the analog FM stereo. The probability of both channels being effected by multipath at the same time is low. It is clear that for this system to operate, the same program must be transmitted on the analog and digital channels. This is a new feature. Figure 1 is a plot of FM-1 with the new system overlaid.

Diversity Sideband IBOC Proposal (USADR ITU paper)

As with the Westinghouse proposal the complete digital signal is duplicated in each sideband. The system will operate on the alternate sideband when 1st and/or 2nd adjacent interference is present. To reduce digital interference to host FM, the two independently modulated digital signals start at ±129 kHz and extend ±200 kHz from the FM channel center frequency. This avoids the 114 kHz interference band described in the compatibility section (II) of this paper. To further reduce interference to the adjacent analog channels, the power of the independent sidebands will be determined by a compromise between digital coverage and adjacent channel interference. Figure 2 is a plot of AT&T/Amati System with the proposed system overlaid.

USADR FM-1 (Lab Tested)

The composite DAR/FM signal in this IBOC system is intended to conform to the FCC PSD masks. The FM-1 stereo audio source coding rates vary from a minimum of 128 kbps to a maximum of 256 kbps on a frame-by-frame basis. The FM-1 IBOC system uses 48 spread spectrum data subchannels. The data rate for each channel is 8 kbps, for a total of 384 kbps. The symbol duration is 125 microseconds. For this system 48 subchannels are used. In addition, a 49th subchannel is transmitted as a training signal for multipath equalization.

The IBOC digital signal is located in a 100 kHz wide sideband that runs from 120 kHz to 220 kHz above and below the FM channel center frequency for a total composite channel bandwidth (3 dB) of 440 kHz. The digital signal average power was set at 15 dB below the host FM for the laboratory tests. Figure 3 is a spectrum analyzer plot of this system's composite baseband signals.

AT&T/Amati/Lucent Technologies (DSB)

The composite DAR/FM signal in the AT&T/Amati IBOC System is intended to conform to the FCC PSD masks. Digital audio coding is provided by the AT&T Perceptual Audio Coder (PAC) which provides a 160 kbps digital signal for a stereo audio channel. The IBOC signal uses discrete multitone or COFDM modulation. The subcarrier spacing is 4 kHz. The symbol duration is 250 microseconds with 32 subcarriers using differential 4-phase modulation.

The digital signal is located in a 73.5 kHz wide sideband that runs from 126.5 kHz to 200 kHz above and below the FM channel center frequency. The total composite bandwidth is 400 kHz. The signal average power was set at 15 dB below the host FM. Figure 4 is a spectrum analyzer plot of the AT&T/Amati signal.

AT&T/Amati/Lucent Technologies (LSB)

The second IBOC system proposed by AT&T/Amati was a single sideband IBOC system. By placing the complete digital signal on one sideband, this system is intended to work in situations where 1st adjacent channel interference is present on the alternate sideband. The equipment that was delivered to the DAR laboratory for testing was capable of operating in three modes, Double SideBand (DSB), Lower Sideband (LSB), or Upper Sideband (USB). The system was tested in the DSB and LSB modes. In Lower SideBand (LSB) mode the digital signal is transmitted in a single 73.5 kHz wide sideband that runs from 126.5 kHz to 200 kHz below the FM channel center frequency. The total composite bandwidth is 300 kHz. The signal average power was set at 24 dB below the host FM. The IBOC signal uses discrete multitone or COFDM modulation. In the LSB or USB modes, 18 subcarriers with 8-phase modulation is used. Digital audio coding is provided by the AT&T Perceptual Audio Coder (PAC) which operates at 128 kbps for the stereo audio digital channel. Figure 5 is a spectrum analyzer plot of the AT&T/Amati signal.

II. Compatibility for Proposed System

D -> Host Analog

Several different forms of decoding circuits have been used for decoding FM stereo. In practice the PLL stereo decoder has become the norm. Because the PLL stereo decoder uses square wave switching, this circuit will demodulate baseband signals which are at the odd harmonics of 38 kHz (3 X 114 kHz and 5 X 190 kHz). These frequencies are in the band used for the transmission of IBOC digital signals. Without special receiver circuitry (114 kHz LP filters or Walsh function PLL decoder), the stereo decoders will detect the IBOC digital signal as noise. To further understand this phenomena, a special receiver test was conducted at the DAR laboratory without the need of a DAR signal. The tests were designed to determine which receivers were sensitive to the digital signal at 114 kHz, and compare those results with the results of the IBOC tests. For the first part of the tests a CW subcarrier was added to the FM signal at 113 kHz with 10% injection, and the receiver audio output noise measured. The subcarrier was offset from the odd harmonics of 1 kHz, so that receivers sensitive to these frequencies would produce a beat 1 kHz tone. Auto receivers #1 and #5 showed little change in S/N with either the 113 kHz tests or the IBOC signals. These receivers employed the Walsh function decoders. Receivers #2, #3, and #4 did not employ Wash function decoders or 114 kHz baseband filters and exhibited a large increase in audio noise with the 113 kHz subcarrier and the IBOC systems. The results of these laboratory tests are shown in Table 1.

Table 1.	IBOC DAR -> Host FM RMS Noise Signal Level -47 dBm				
Receiver	Type Radio	S/N FM Only Reference	S/N 114 kHz Test	S/N AT&T/Amati DSB	S/N USADR FM-1
1. Delco 161924463	Auto	60.0 dB	No Change	60.7 dB	60.3 dB
2. Denon TU-280RD	Hi-Fi High End	68.0 dB	34.0 dB	50.0 dB	44.9 dB
3. Panasonic RX-PS430	Stereo Portable	67.5 dB	33.6 dB	44.2 dB	42.0 dB
4. Pioneer SX-201	HI-Fi	66.0 dB	33.1 dB	40.0 dB	39.2 dB
5. Ford F4XF-19B132-CB	Auto	65.0 dB	No Change	64.0 dB	62.7 dB

Additional IBOC to Host Lab Tests

The first additional test was designed to compare the receiver sensitivity to interference at 114 kHz, to the sensitivity at 190 kHz. The test was the Denon TU-380 (RBDS) home Hi-Fi receiver. This tests were conducted in two modes and at two frequencies: the first using a single subcarrier at 113 kHz and 189 kHz and the second using a single transmitter separated from the main carrier by -113 kHz and -189 kHz. The results of this test revealed that this radio's sensitivity to this interference at the two frequencies is within 2 dB or less, depending on the transmission mode.

The TU-380 receiver was selected because it was the PLL receiver least sensitive to the IBOC digital noise during the DAR laboratory tests (Table 1.).

The second additional test was designed to further investigate this interference. If the above tests are accurate, it would follow that the frequency band between the two sensitive frequencies, less 15 kHz for (L-R) audio modulation, should be free of PLL stereo decoder interference. This frequency band is centered at 152 kHz with a bandwidth of no more than 46 kHz. This test used the Denon TU-360 receiver and a separate CW transmitter operating at a frequency -152 kHz below the FM channel center frequency. The CW signal did not effect the receiver S/N ratio. FM Modulation with +/- 20 kHz deviation was then applied to the transmitter. This resulted in an RMS S/N of 61 dB on the TU-360 receiver, 23 dB better than the tests with the CW signals at 113 kHz and 114 kHz. See Appendix 1 for test details.

The DAR tests have shown that receivers with un-filtered PLL stereo decoders have two 30 kHz wide bands of frequencies (centered at 114 kHz and 190 kHz) that are sensitive to interference. This test revealed that these bands are nearly equal in sensitivity to interference.

Figure 4 shows a plot of the AT&T/Amati IBOC signal, and Figure 3 the FM-1 systems. The digital PSD for both systems is shown. The 114 kHz and 190 kHz PLL receiver sensitive bands are noted on the upper sidebands. The AT&T/Amati plot (Figure 4.) shows that at 114 kHz the digital signal is down by 23 dB, and at 190 kHz the digital signal is at full amplitude. It can also be seen on the FM-1 plot (Figure 3) that the 114 kHz digital signal is 10 dB down, and the 190 kHz is at full amplitude. The results of the digital -> host analog test (Table 1.) show that even if the system avoided the 114 kHz band, the system had similar noise increase. It can be concluded that for the Amati/AT&T System the 190 kHz frequency band was the major contributor to the noise floor increase.

Diversity Sideband to Host Analog (Westinghouse Proposal)

This proposal substantially changes the frequency spread and power level of the digital sideband signal's. The power is reduced by 6 to 10 dB below the FM-1 levels. The digital signals frequency would be transmitted in two bands 100 kHz wide and run from 100 kHz to 200 kHz above and below the channel center frequency. It can be seen from the results of the above test that many of the compatibility advantages of the proposed digital power reduction may be offset by the transmission of a full amplitude digital signal at 114 kHz.

Diversity Sideband to Host Analog (ITU Proposal)

To avoid noise this proposal avoids the 114 kHz band by starting the digital signal at 129 kHz and running it up to 200 kHz above and below the carrier. This avoids the 114 kHz band but transmits a full level signal at 119 kHz. The compatibility tests show that the receivers are also sensitive to the 190 kHz band and avoiding only the 114 kHz band will not solve the IBOC digital -> to host analog compatibility problem.

III. Adjacent Channel Performance

First Adjacent A -> D (Westinghouse Proposal)

The major interferer for the sideband IBOC digital signal is the first adjacent analog. The FCC protects the FM station with a D/U of 6 dB (desired 6dB above undesired). This system proposes to set the digital signal power 21 to 25 db below the FM. The FM-1 and AT&T/Amati DSB laboratory tests were conducted at power level 6 to 10 dB higher than the proposed power. For comparison the A -> D first adjacent of 23 dB D/U at TOA will be used. This was the best first adjacent measured in the laboratory (AT&T/Amati DSB). To reduce the power will increase the D/U to a range of 29 to 33 dB without multipath. These D/U ratios exceed the FCC figures by 23 to 27 dB.

Second Adjacent D -> D (Westinghouse Proposal)

Because the sideband IBOC systems occupy a 400 kHz composite channel, the second adjacent FM station D/U criteria is in reality a digital first adjacent problem. This means that the IBOC systems will have to exist in an established FM second adjacent environment with D/Us of up to -40 dB. Both IBOC proposals have eliminated the FM-1 overlap by moving the digital signal within the outer edge of the first adjacent channel (200 kHz). In the laboratory tests the AT&T/Amati System had the best second adjacent performance without multipath, -17.5 dB at TOA, and -21 dB at POF. With multipath the system's susceptibility to second adjacent interference will be significantly increased.

D -> Adjacent Channel FM (Westinghouse Proposal)

The 6 to 10 dB reduction in the digital sideband power will reduce the interference to the first and second adjacent channels. The change in interference is receiver dependent. The calculated changes in interference to the first adjacent channel for each receiver are shown in Table 2.

The AT&T/Amati System is used for the adjacent channel calculations because its interference into the adjacent channel is similar in the Westinghouse proposal. The calculated changes in interference to the second adjacent channel for each receiver are shown in Table 3.

Table 2. First Adjacent (Westinghouse Proposal)
Digital -> Analog

Receiver	AT&T/Amati more sensitive to interference in D/U (reference) (Ref/System)	Calculated Westinghouse -21 dB SB power (Ref/System)	Calculated Westinghouse -25 dB SB power (Ref/System)
Delco	15 dB Non-Linear	9 dB	3 dB
Denon	10 dB Linear	4 dB	0 dB
Panasonic	2 dB Linear	0 dB	0 dB
Pioneer	4 dB Linear	0 dB	0 dB
Ford	26 dB No Test	20 dB	16 dB

Table 3. Second Adjacent (Westinghouse Proposal)
Digital -> Analog

	AT&T/Amati more sensitive to interference in D/U (reference) (Ref/System)	Calculated Westinghouse -21 dB SB power (Ref/System)	Calculated Westinghouse -25 dB power (Ref/System)
Delco	0 dB Linear	0 dB	0 dB
Denon	10 dB Slight NL	4 dB	0 dB
Panasonic	15 dB Linear	9 dB	5 dB
Pioneer	12 dB Linear	6 dB	2 dB
Ford	15 dB No Test	9 dB	5 dB

IV. Composite Digital Signal Performance

Westinghouse Proposal

With the bandwidth of the signal limited to 100 kHz and the reduction of the digital signal power by 6 to 10 dB, the coverage area, immunity to multipath, and the immunity to analog interference will be reduced. With the diversity proposal the complete stereo program signal is transmitted on three separate channels; lower digital sideband, upper digital sideband, and analog. Assuming the loss of one of the digital channels, the receiver will switch to the other digital channel. If both sidebands are interfered with, the receiver will switch to the FM analog channel. To cover the effects of switching from digital to analog, the quality of the FM analog channel will have to match the digital.

The audio processing for the FM analog audio channels will be significantly different than the ideal for digital. FM analog processing is designed to cover problems caused by pre-emphasis, noise, and system limited dynamic range. These problems will not be found in the digital channel. The use of the switch to analog to cover multipath problems or interference to the digital channel may be complicated by the different sound quality of the two transmission mediums. Compromises in processing the analog FM and digital channels to match the sound may prove to be the only solution. This would mean that the new digital service will sound just like the FM analog service.

V. FM Signal Levels and the Impact on the Proposed IBOC Systems

Introduction

To understand the environment the IBOC systems will have to operate in, measurements were made at several locations of FM broadcast signal levels throughout the 88-108 Mhz FM band. These measurements are to help determine existing spectrum occupancy with particular attention to signal ratios with varied signal adjacencies.

Methods

Measurements were made from a parked automobile with a 1/4 wave vertical antenna mounted on the roof (four feet above road). The FM receiver seek tuning mode was used for station selection. In the seek mode the receiver stopped for signals as low as -76 dBm at the receiver input. At this signal level the test receiver was in full blend (no stereo). Only the data from listenable signals was used (CCIR impairment level of 3, slightly annoying). Five representative graphs show the results of measurements at the five sites (Graph 2 through 6) selected from a field of 38 chosen to illustrate potential adjacent channel interference to IBOC digital reception in congested areas.

Discussion

The performance of IBOC DAB systems depends on the specific protection ratios for the first and second adjacent channels, as measured at the input terminals of the DAR receiver. Because FM band analog transmitting power levels are set by regulatory limits, analysis of band-wide signal level measurements at fixed locations will show the anticipated performance for DAB systems with adjacent channel interference.

Analysis

The following procedure is used for analyzing the performance of the proposed IBOC systems using the signal level RF measurements. The adjacent channel D/Us for the AT&T/Amati System are used for this analysis. Of the IBOC systems tested, this system was the least susceptible to adjacent channel interference and had the best IBOC measured performance characteristics.

Laboratory Test Results

1) first adjacent channel -- Without multipath the analog-to-digital laboratory tests measured a 23 dB D/U at TOA. Using the least aggressive multipath scenarios, the TOA D/U averaged 30 dB. With the proponents 6 dB power reduction, the first adjacent D/U is 36 dB for analysis.

2) second adjacent channel -- Without multipath the digital-to-digital laboratory

tests measured a -17.5 dB D/U at the TOA. With multipath factor added a -10 dB D/U is used for the analysis.

Table 4 shows the location of each test site, the number of FM stations listenable at each site, number of stations received with D/U that are out of FCC specifications, predicted number of digital signals received without interference, predicted number of digital signals received with one digital sideband, and number of receivers with interference on both digital sidebands (analog only). The letters in the table indicate receiver mode.

Receiver modes
A. Two digital and analog without interference
B. One digital and analog without interference
C. Analog only

Table 4. Number of stations

Site State	#FM stations received	Stations received with D/U outside FCC	Mode A Predicted number of stations received both sidbands & analog	Mode B Predicted Stations received in only one digital sidebands & analog	Mode C Predicted Stations with both sidebands interfered with (analog only)
1 VA	31	1	22	5	4
7 VA	35	4	23	8	4
10 MD	38	2	24	9	5
16 MD	47	14	23	17	7
10 NJ	47	25	13	25	9

VI Conclusions

Table 5 Conclusions

IMPAIRMENT	Westinghouse Proposal	UDADR ITU Proposal
Digital -> Host Analog Reference section II, page 3	Some improvement, but will not eliminate noise. Noise may not decrease linearly with digital power reductions.	Little change, system waveform is similar to AT&T/Amati waveform. Sideband power may be independently varied for coverage or interference.
Digital -> 1st Adj Analog Reference page 6 & Table 2	All interference reduced by 6 or 10 dB. First adj interference 9 dB worse than reference analog on Delco auto receiver. First adj interference 20 dB worse than reference analog on Ford auto receiver. Little to no interference on home receivers.	Little change, system waveform is similar to AT&T/Amati waveform. Interference should be similar to the AT&T/Amati interference listed in Table 2. Most adj channel interference should be found on narrowband auto receivers.
Digital -> 2nd Adj Analog Reference page 7 & Table 3	Improvement dependent on power reduction.	Little change, similar to AT&T/Amati. Four of the five receivers tested had 2nd adj interference from AT&T/Amati.
Analog -> 1st Adj Digital (Digital -> Digital 1st Adj similar problem) Reference page 5, section III	First adj analog is major interferer. Will force receiver diversity to operate. Sideband will require 29 to 33 dB D/U protection. FCC protection is 6 dB.	If power is reduced to protect adj station or improve compatibility, system will become more sensitive to first adj analog or first adj IBOC interference.
Analog -> 2nd Adj Digital Ref EIA DAR Lab Test Report	With a reduction in power, 2nd adj analog channel will become a problem for the desired digital signal.	Is a minor problem. If power is reduced second adj interference may be a problem.
Multipath Reference page 7, section IV	The diversity system is intended to switch to time delayed analog audio to hide the effects of in motion multipath. System will not operate when vehicle is not in motion. Matching the analog to digital audio quality will be a problem.	Not detailed in paper. If delayed analog audio is used, system will have same problems as the Westinghouse Proposal.
Diversity activation with interference Reference page 8 & 9, section V & Table 4	Table 4 shows five test sites where 198 stations were listenable. Interference should activate the diversity system for 93 of these stations. Tests were conducted in heavily populated areas.	If power is not reduced, system will be a little less sensitive to adj channel interference than with the Westinghouse proposal.

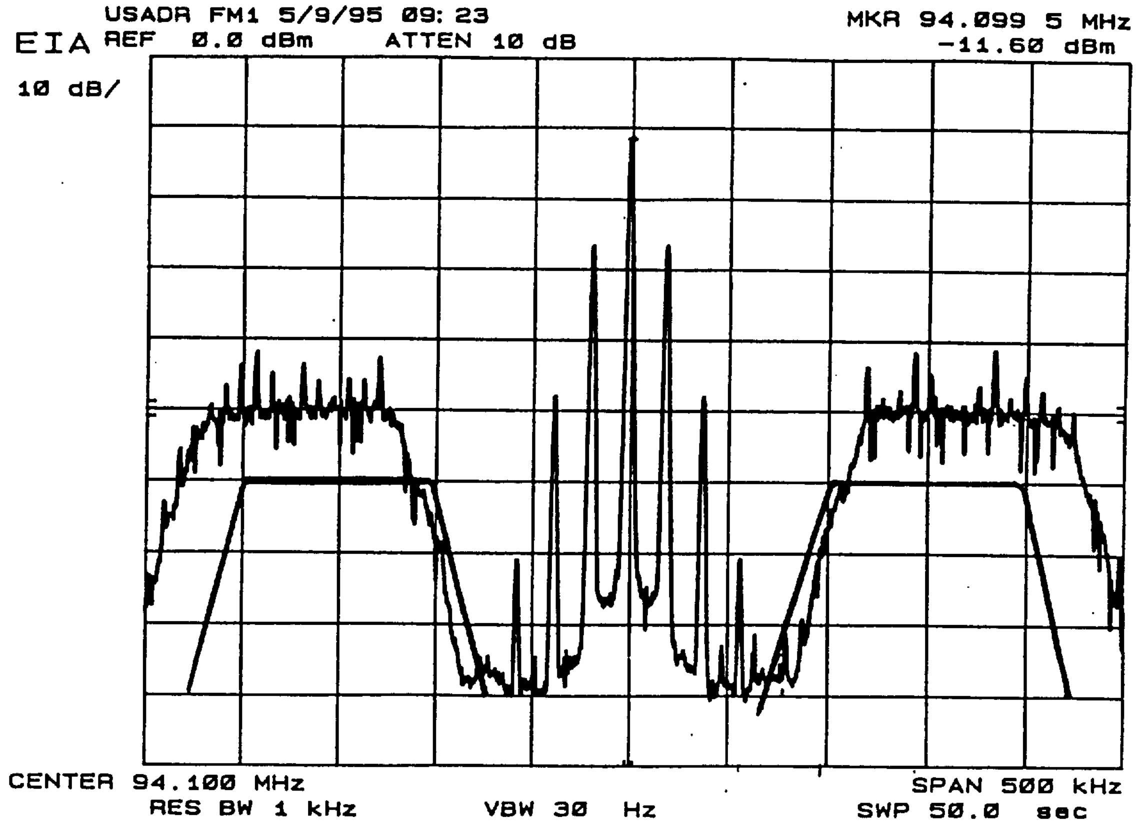


Figure 1 FM-1 with Westinghouse Proposal Overlaid

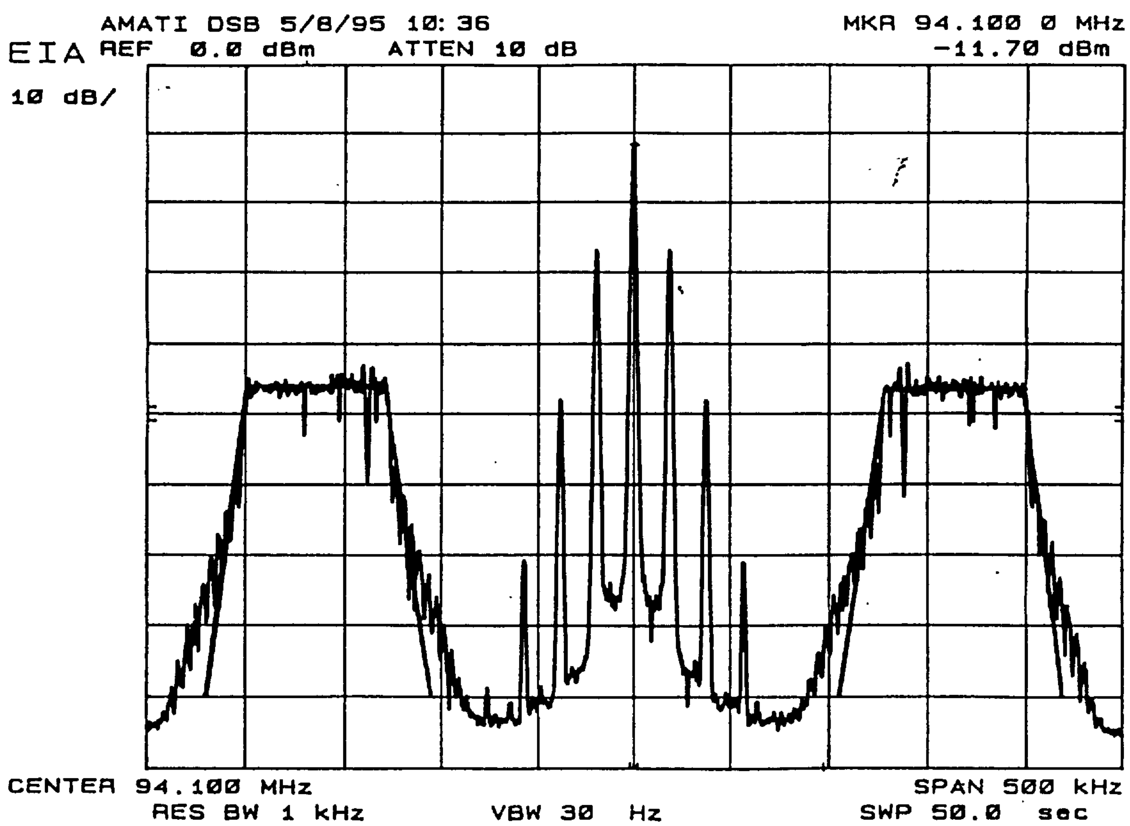


Figure 2 AT&T/Amati with USADR ITU Proposal Overlaid

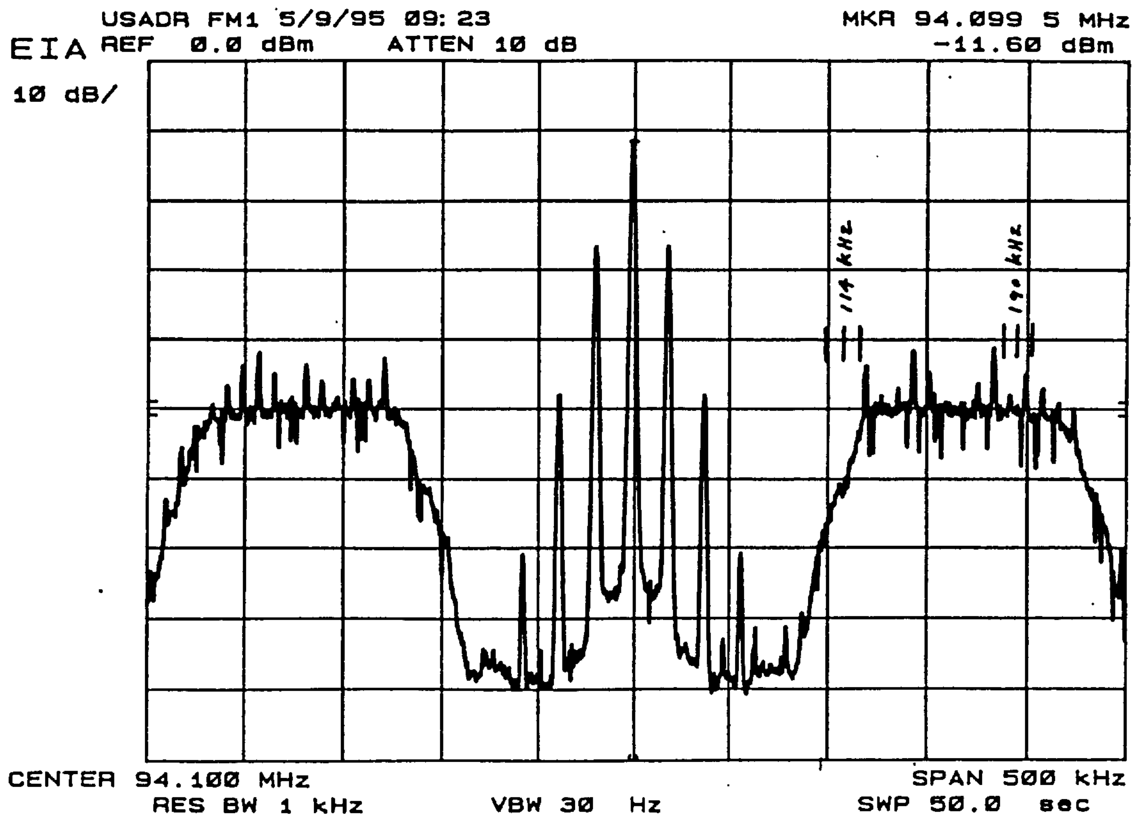


Figure 3 USADR FM-1 System

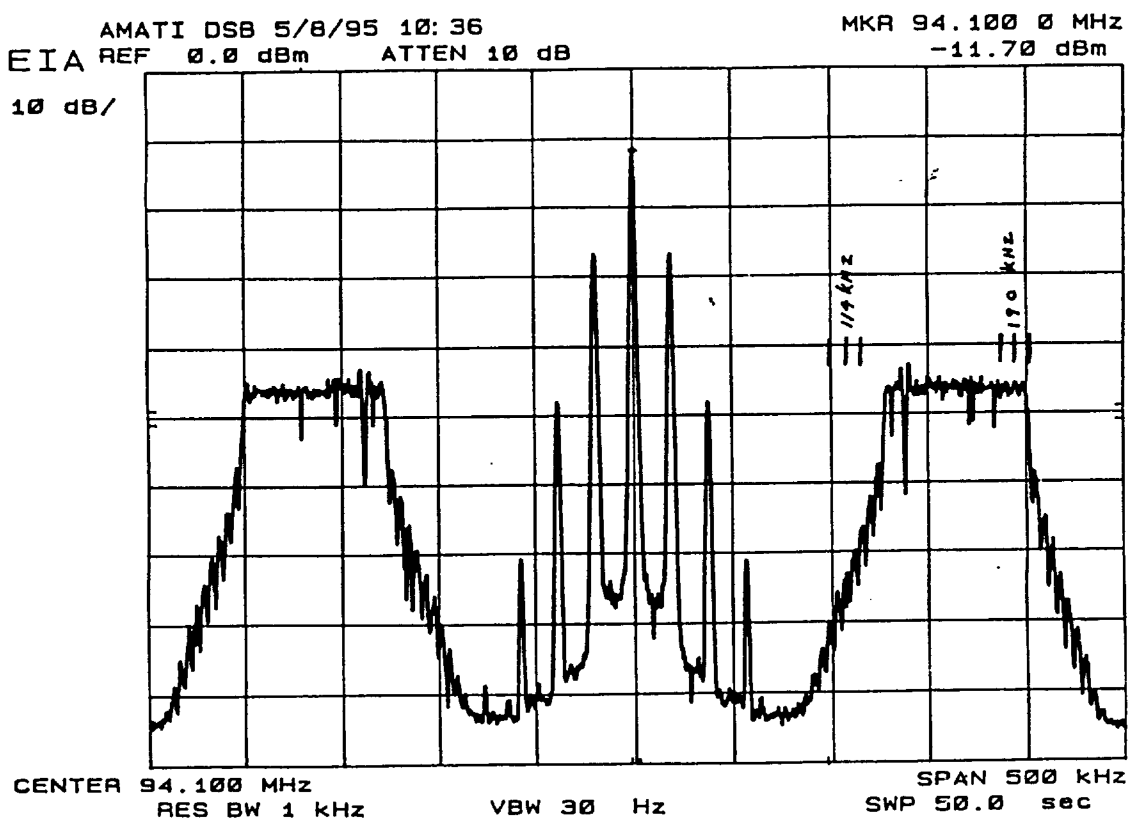


Figure 4 AT&T/Lucent/Amati DSB System

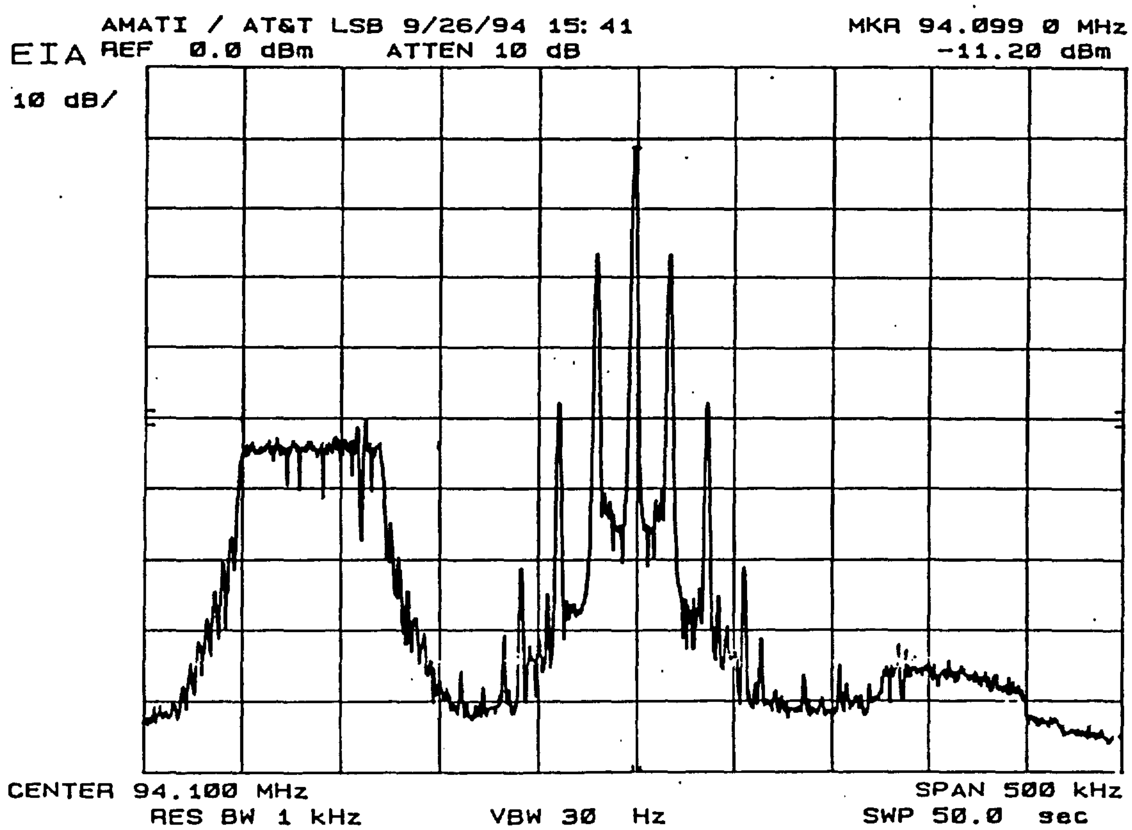
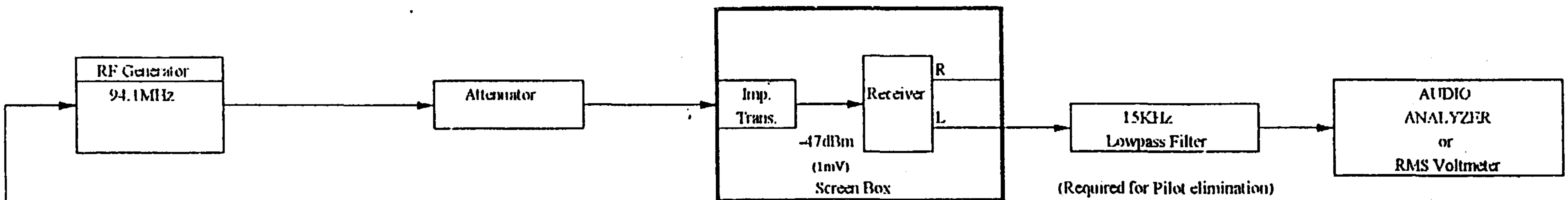


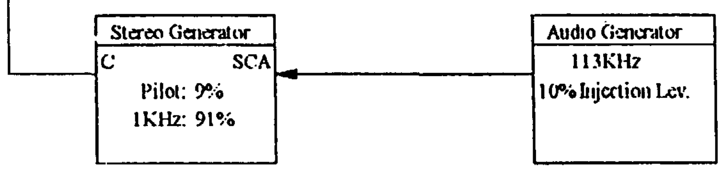
FIGURE 5 AT&T/LUCENT/AMATI LSB SYSTEM

APPENDIX 1

WALSH FUNCTION TEST

EIA Digital Audio Radio Test Laboratory





Receiver: Denon TU-380 Serial: 4056301149

RESULTS	1KHz Reference		113KHz Test	
Measurement	ON	OFF	ON	[redacted]
Enter-> (Volts)	0.67	0.00022	0.012	[redacted]
S/N Ratio (dB)	0	69.67	34.94	[redacted]

Date: Sept. 28/95 Engineer: RMc

The above set up will test for the presence of either a Walsh Function type stereo decoder or a decoder using a filter to reduce interference at and above 114KHz
The test injects 113KHz to heterodyne or "beat" with any 114KHz component. If the 114KHz component is present a 1KHz tone will result and thus degrade the S/N ratio.

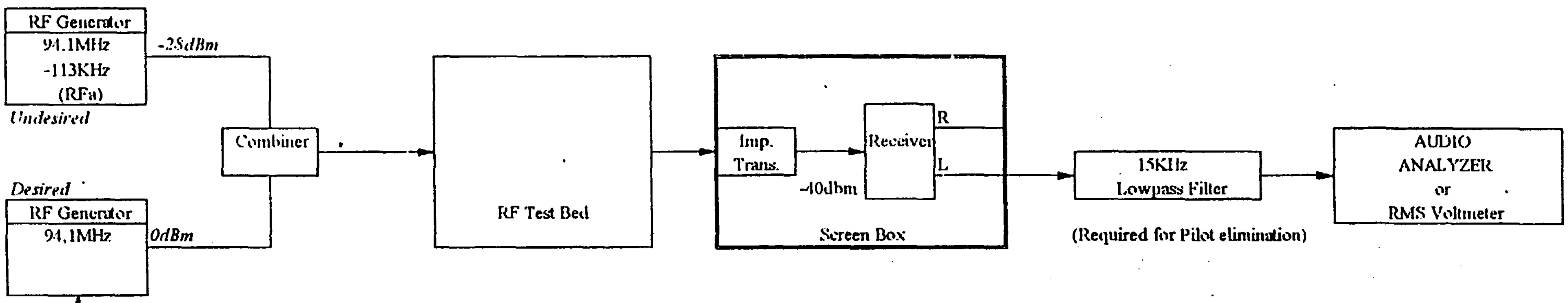
1) Using an audio analyzer or RMS voltmeter, measure the receiver output with a 1KHz @ 91% and 19KHz @ 9% modulation signal.
Enter the result (in volts) in the 1KHz Reference "ON" column. This will establish the 0dB stereo reference.

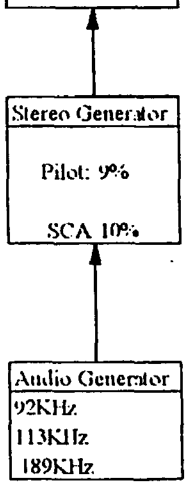
2) Turn off the 1KHz and record the measurement (in Volts) in the 1KHz Reference "OFF" column. The Stereo Signal to Noise Ratio will be calculated.

3) Turn on the 113KHz tone (at 10% injection) and measure the receiver output. Record the result (in Volts) in the 113KHz Test "ON" column.
The new Signal to Noise ratio will be calculated. This figure will show whether or not the receiver is sensitive to interference from 99KHz to 129KHz.

Receivers with no filtering or Walsh type decoders will typically show a reduction in S/N ratio with the presence of 113KHz on the order of 20 to 30dB.
Receivers with filters or Walsh type decoders will show little (5dB) to no difference in S/N ratio.

EIA Digital Audio Radio Test Laboratory

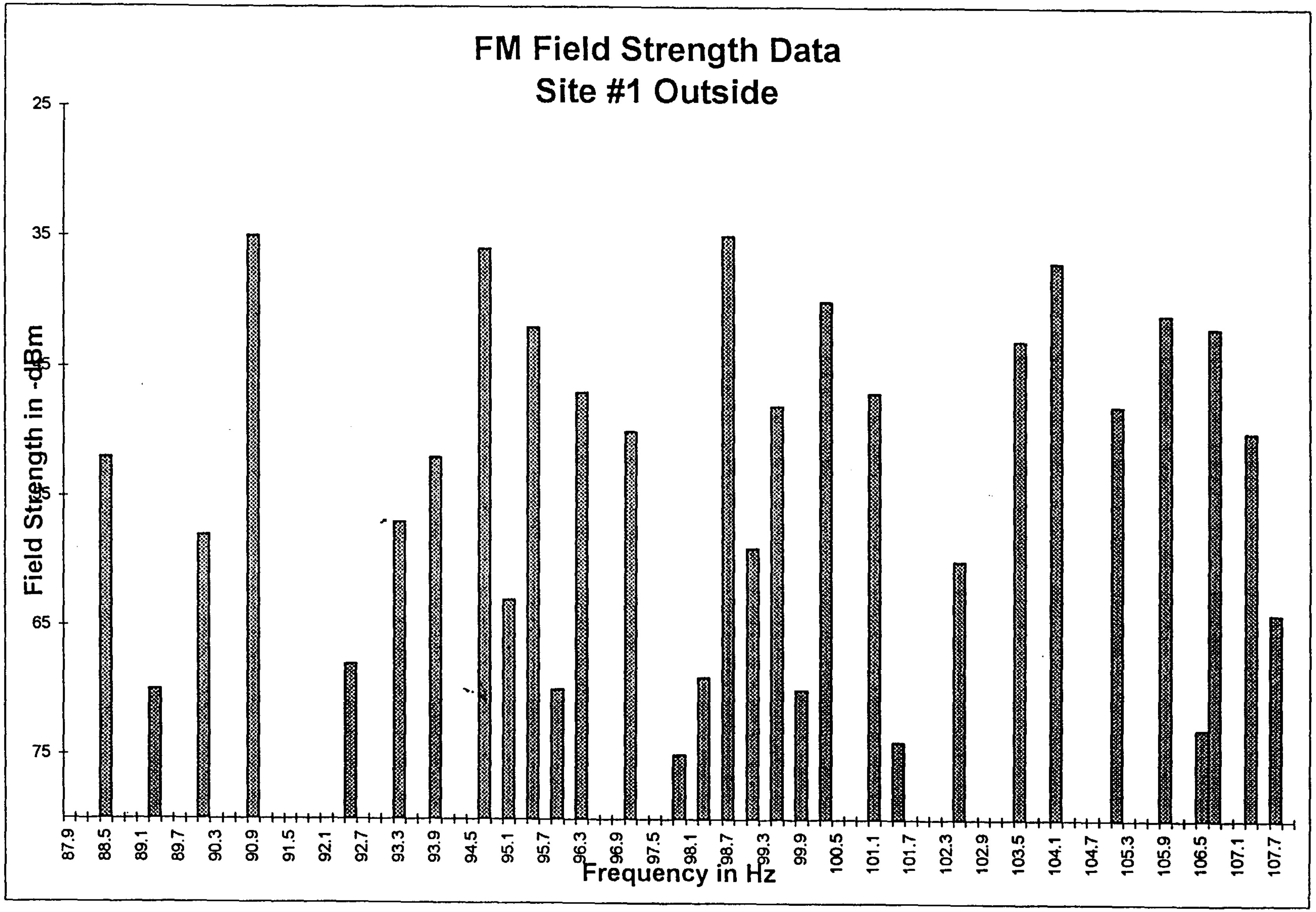




Date: 10/23/95 Engineer: RMc
Receiver: Denon TU-380 Serial: 4056301149

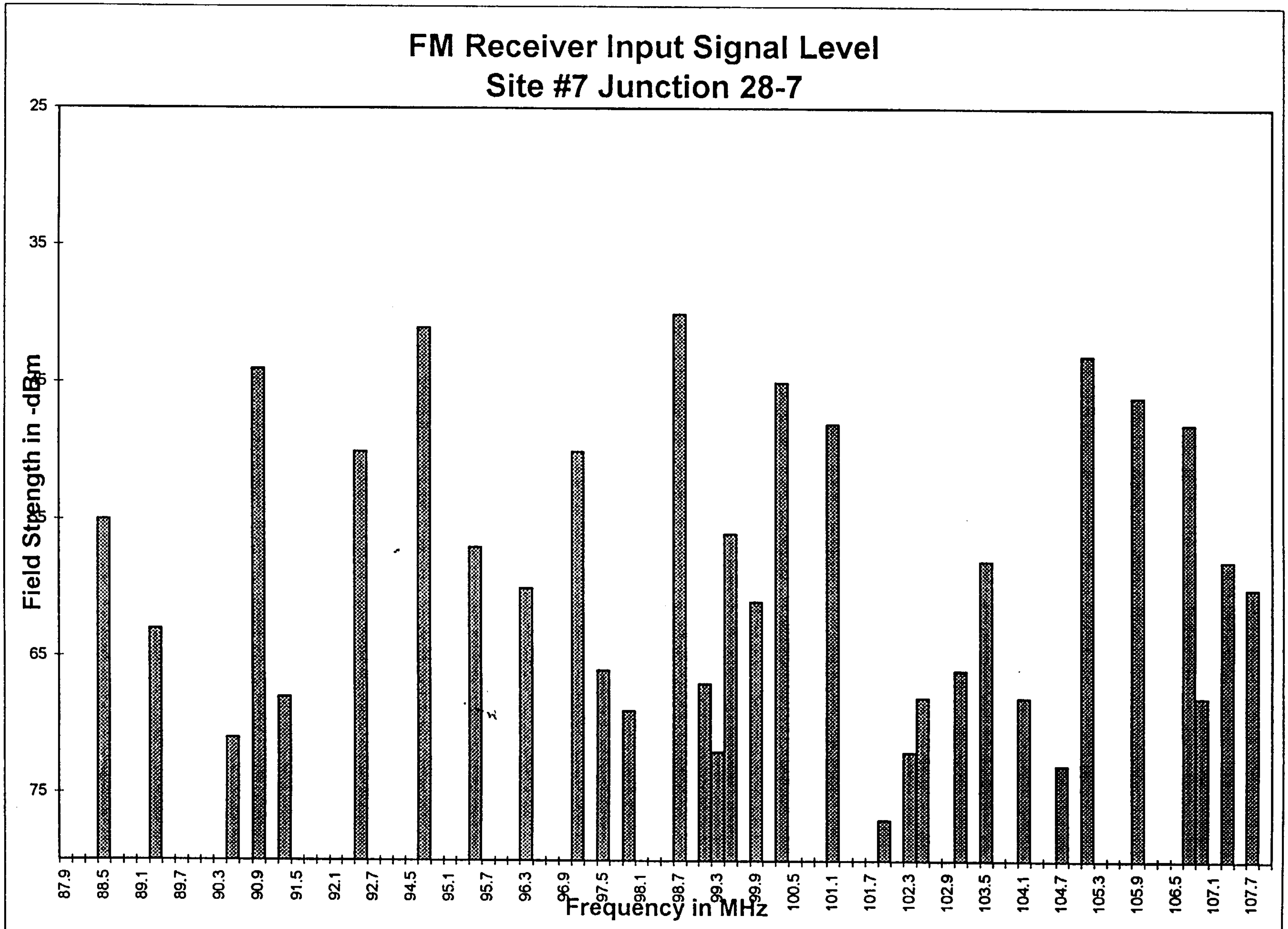
Signal	S/N Ratio (dB) RMS	Qpk/W	
Normal	69	61.5	
W/92KHz	65		
W/113KHz	38		
W/189KHz	40		
W/RFa	38		--- (94.1MHz @ -40dBm) + (94.1MHz - 113KHz @ -68dBm)
W/RFb	38		--- (94.1MHz @ -40dBm) + (94.1MHz - 189KHz @ -68dBm)
W/RFc	68	61	--- (94.1MHz @ -40dBm) + (94.1MHz - 152KHz @ -68dBm)
W/RFc	61	51.1	--- (94.1MHz @ -40dBm) + (94.1MHz - 152KHz @ -68dBm Modulated +/-20KHz)

Modulation of the undesired signal with 400Hz +/- 20KHz to create interference in the desired signal from 129KHz to 175KHz. Less modulation caused much less noise. More modulation caused much more noise indicating a fairly sharp knee and the presence of a "hole" between 129KHz and 175KHz

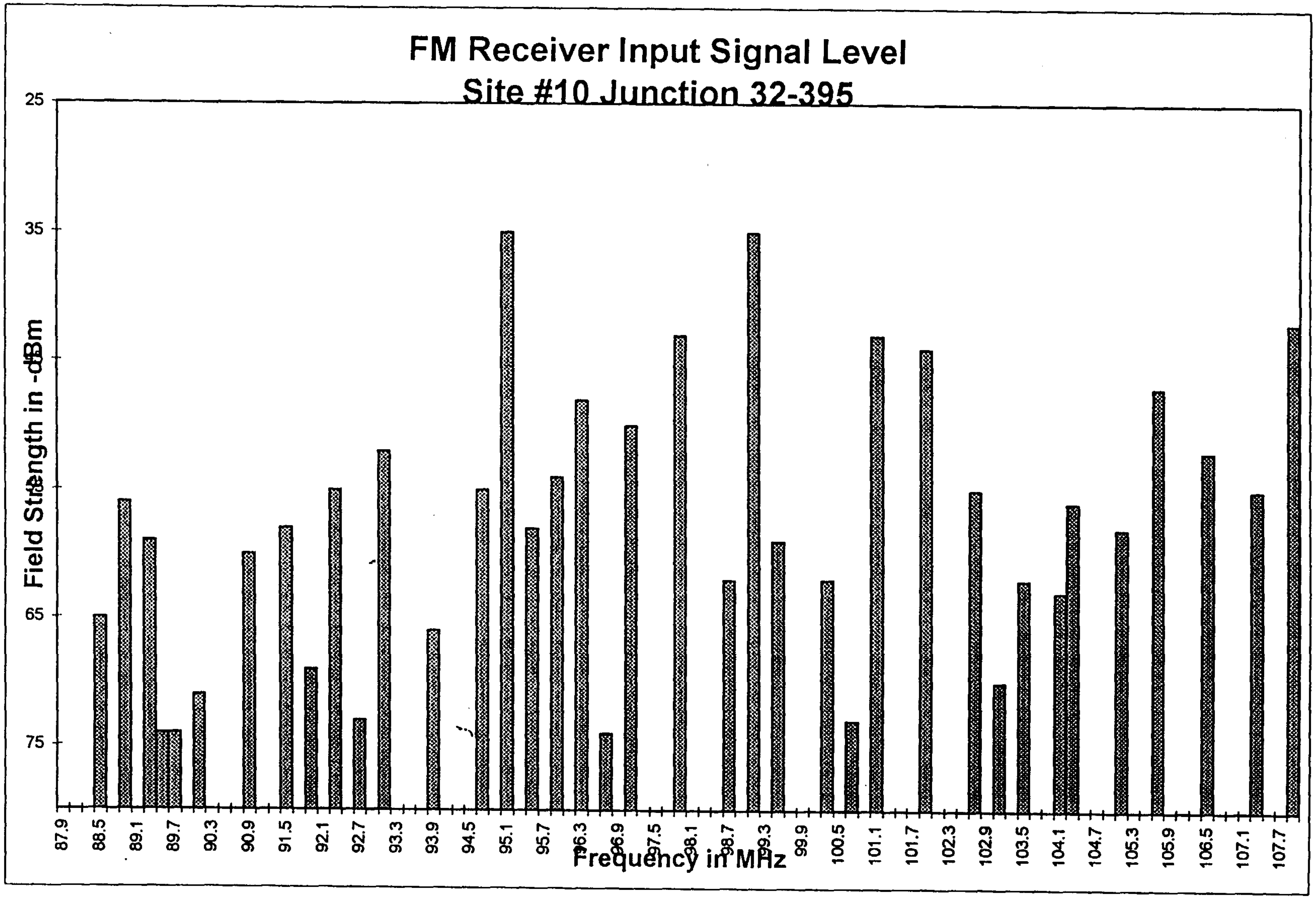


FM Field Strength Data
Site #1 Outside
Field Strength in -dBm
25
35
65
75
87.9
88.5
89.1
89.7
90.3
90.9
91.5
92.1
92.7
93.3
93.9
94.5
95.1
95.7
96.3
96.9
97.5
98.1
98.7
99.3
99.9
100.5
101.1
101.7
102.3
102.9
103.5
104.1
104.7
105.3
105.9
106.5
107.1
107.7
Frequency in Hz

Graph 1

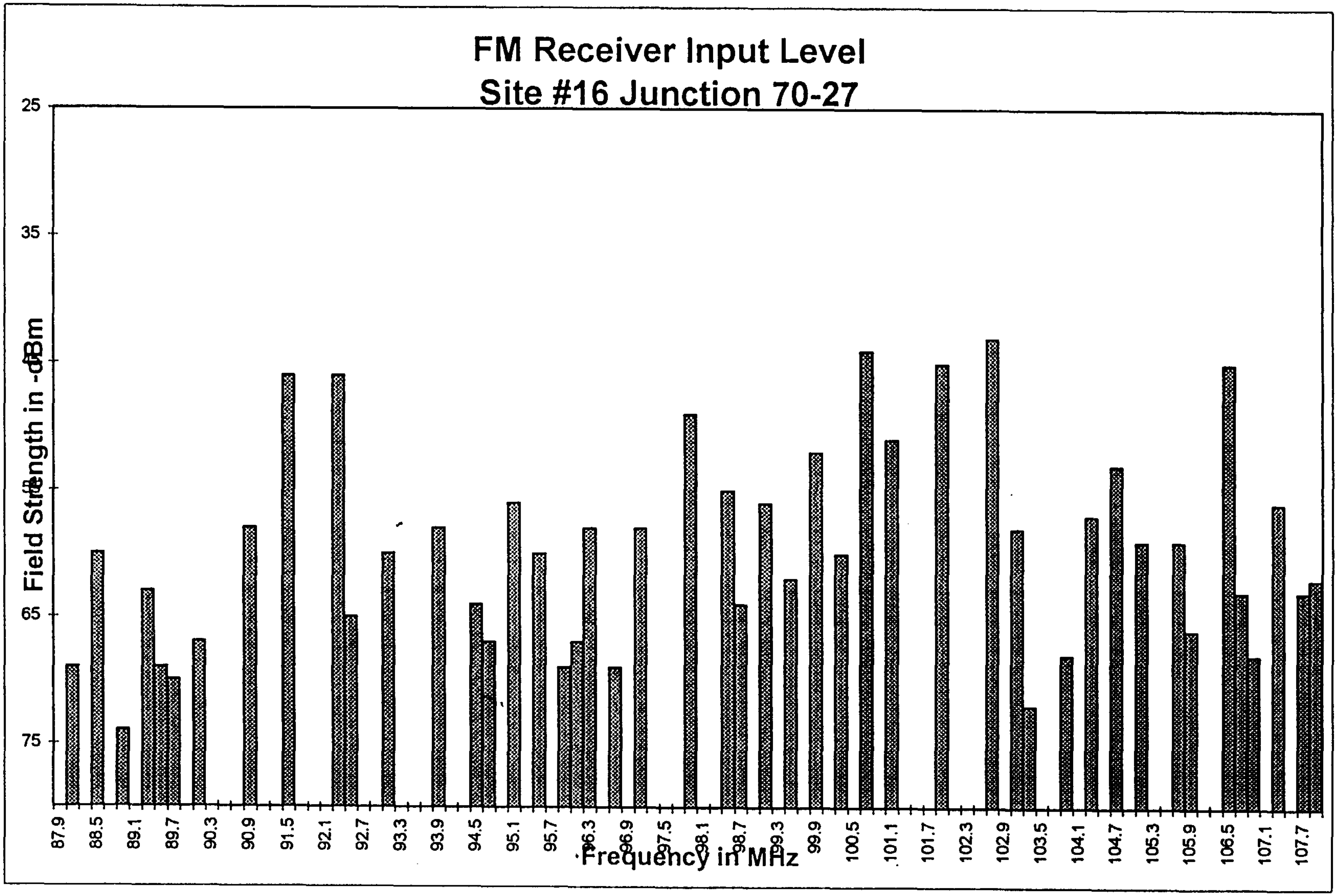

FM Receiver Input Signal Level
Site #7 Junction 28-7
25
35
65
75
Field Strength in -dBm
87.9
88.5
89.1
89.7
90.3
90.9
91.5
92.1
92.7
94.5
95.1
95.7
96.3
96.9
97.5
98.1
98.7
99.3
99.9
100.5
101.1
101.7
102.3
102.9
103.5
104.1
104.7
105.3
105.9
106.5
107.1
107.7
Frequency in MHz

Graph 2

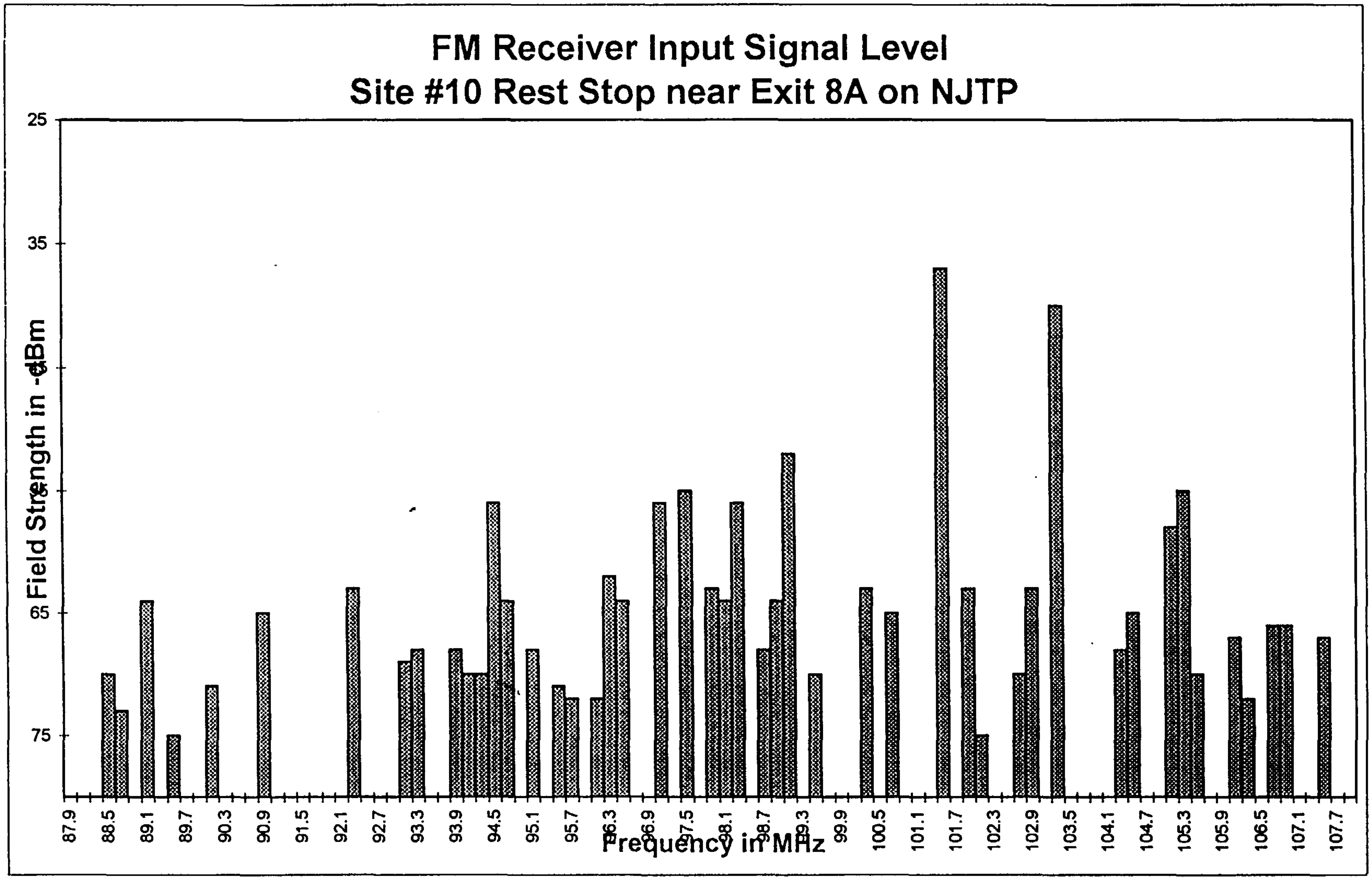


FM Receiver Input Signal Level
Site #10 Junction 32-395
Field Strength in -dBm
25
35
65
75
87.9
88.5
89.1
89.7
90.3
90.9
91.5
92.1
92.7
93.3
93.9
94.5
95.1
95.7
96.3
96.9
97.5
98.1
98.7
99.3
99.9
100.5
101.1
101.7
102.3
102.9
103.5
104.1
104.7
105.3
105.9
106.5
107.1
107.7
Frequency in MHz

Graph 3


FM Receiver Input Level
Site #16 Junction 70-27
Field Strength in -dBm
25
35
65
75
Frequency in MHz
87.9
88.5
89.1
89.7
90.3
90.9
91.5
92.1
92.7
93.3
93.9
94.5
95.1
95.7
96.3
96.9
97.5
98.1
98.7
99.3
99.9
100.5
101.1
101.7
102.3
102.9
103.5
104.1
104.7
105.3
105.9
106.5
107.1
107.7

Graph 4


FM Receiver Input Signal Level
Site #10 Rest Stop near Exit 8A on NJTP
Field Strength in -dBm
25
35
65
75
87.9
88.5
89.1
89.7
90.3
90.9
91.5
92.1
92.7
93.3
93.9
94.5
95.1
95.7
99.9
100.5
101.1
101.7
102.3
102.9
103.5
104.1
104.7
105.3
105.9
106.5
107.1
107.7
Frequency in MHz

Graph 5